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From strange to charmed baryons using two-flavour QCD

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Abstract

We compute the mass spectrum for strange and charmed baryons in the partially quenched approach using $N_f = 2$ twisted mass QCD configurations. We investigate two main issues: the size of lattice artefacts using three values of the lattice spacing (the smallest of which is approximately 0.05 fm) and the dependence of baryon masses on meson masses. We thus perform a global fit in order to extrapolate simultaneously to the continuum limit and to the physical point. We obtain predictions for the Ω_{sss} , Ξ_{dss} , Λ_{uds} , Ω_{ccc} , Ξ_{dcc} , Λ_{udc} masses.

Keywords: Lattice QCD, twisted mass, baryon physics

1. Introduction

Lattice regularization of QCD offers the unique opportunity of computing non-perturbative quantities like the hadron spectrum, decay constants, weak matrix elements and form factors from first principles. Using this regularization, the functional integral can be in fact evaluated numerically through Monte Carlo simulations. Numerical simulation are performed for a range of values of the lattice spacing a and of the quark masses m_q and then have to be extrapolated to the continuum limit and to the physical value of the quark masses.

The inclusion of (light) sea quarks in numerical simulations proves to be particularly challenging and in the past sea quark effects were often neglected, leading to the so-called quenched approximation. Nowadays simulations with two light degenerate sea quarks ($N_f = 2$) and in some cases including also the strange sea quark ($N_f = 2+1$) or both the strange and the charm sea quarks ($N_f = 2 + 1 + 1$) have become standard even though the light quarks are not yet as light as the physical up/down quarks. The difficulty in reaching the physical point is due to the slowing down of Monte Carlo simulations in the critical region and also to the fact that light quarks at the physical point require big volumes in order the observables not to be affected by large finite size effects.

The inclusion of the strange sea quark, due to his heavier mass, is slightly less important and at present there are no striking examples where $N_f = 2 + 1/N_f = 2 + 1 + 1$ simulations gives substantially different results with respect to the $N_f = 2$ case. This is believed to be even more the case for the charm sea quark.

Valence quarks can be treated independently from the sea quarks and can be simulated with the same masses of the sea quarks or with different ones. One can even consider valence quarks which are not present in the sea, for example the strange and the charm quark in the case of $N_f = 2$ simulation. This setup is called partially quenched approximation and we will use it in the present study.

Concerning heavy quarks (e.g. the bottom quark) the compton wavelength of the associated heavy-light meson is too small compared to present attainable lattice spacings. This means that heavy quarks feel discretization effects and related observables can be affected by large lattice artefacts. The charm quark mass is at the upper boundary of the range of masses that can be simulated at present for the coarsest lattice spacing used in the continuum limit extrapolation ($a \sim 0.1$ fm for which $m_c a \lesssim 1$). In order to safely control this extrapolation it is thus important to asses the size of lattice artefacts affecting the observables of interest.

In the present contribution we extend the study of [1] by including a finer lattice spacing $a \simeq 0.051$ fm and we present preliminary results for the masses of some strange baryons (Ω_{sss} , Ξ_{dss} , Λ_{uds}) and the corresponding charmed baryon obtained by substituting all the strange quarks with charm quarks (Ω_{ccc} , Ξ_{dcc} , Λ_{udc}).

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2. Setup

As for the choice of the lattice discretization we choose here twisted mass QCD [2] with two degenerate light flavors. This regularization is attractive for its simplicity and conceptual clarity and its main advantage with respect to the standard Wilson regularization is that the spectrum and the matrix elements extracted from correlation functions are automatically $O(a)$ improved [3], i.e. lattice artefacts start at $O(a^2)$. The drawback is that parity and isospin are explicitly broken by $O(a^2)$ lattice artefacts and are recovered only in the continuum limit. The strange and charm quarks are added here only as valence quarks. We use ETMC configurations generated at three values of the lattice spacing $a \in \{0.051, 0.064, 0.080\}$ fm and physical volumes $L \sim 2.0 \div 2.4$ fm [4]. Light sea quark masses correspond to pion masses $M_\pi \in [290, 520]$ MeV while partially quenched valence strange/charm (in the following called “heavy”) quarks correspond to heavy-light meson masses $M_K \in [520, 710]$ MeV and $M_D \in [1.80, 2.40]$ GeV. In all we have 40 different combinations (M_π, M_{hl}) . In order to combine data at different lattice spacings we express the value of the masses in units of r_0 [5] by multiplying the value in lattice units by the ratio r_0/a . For the three lattice spacings considered here the values $r_0/a \in \{8.36, 6.73, 5.36\}$ are taken from [4].

3. Numerical results

An important issue in our study is the dependence of the baryon masses upon the “heavy” quark mass m_h in the strange and in the charm region. At $a = 0.080$ fm and $M_\pi \approx 340$ MeV this dependence is shown in Fig. 1.

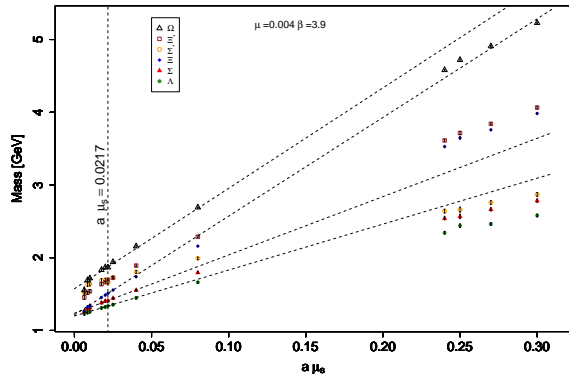


Figure 1: dependence of the octet and decuplet baryon masses on m_h . Dashed lines correspond to linear fits performed in the strange region.

As it will be confirmed in the following, Fig. 1 already suggests that baryon masses depend linearly on

m_h both in the strange and in the charm region but with two different slopes. For what concern meson masses, in the case of the Kaon we observe a dependence $M_K^2 \propto m_h$, in agreement with the fact that the Kaon can still be considered a pseudo Goldstone boson. For the D meson instead we observe a dependence $M_D \propto m_h$ as predicted by heavy quark effective theory (HQET), with no evidence of $1/m_h$ term. In the following we will consider the functional dependence of baryon masses upon M_π and M_{hl} because this allows to extrapolate to the physical point without knowing the values of the renormalized quark masses. The observations above imply that baryon masses depend quadratically on M_K in the strange region while depend linearly on M_D in the charm region.

From Fig. 1 and Fig. 2 it is also evident that the splitting between $J = 1/2$ and $J = 3/2$ states (Σ/Σ^* and Ξ/Ξ^*) clearly diminishes with the increase of m_h . In quark models, this observation is explained thanks to the fact that the spin-spin coupling part of the $q-q$ potential is inversely proportional to the masses of the two quarks $\frac{s_i \cdot s_j}{m_i m_j}$. In HQET the Σ/Σ^* splitting is proportional to $1/m_h$.

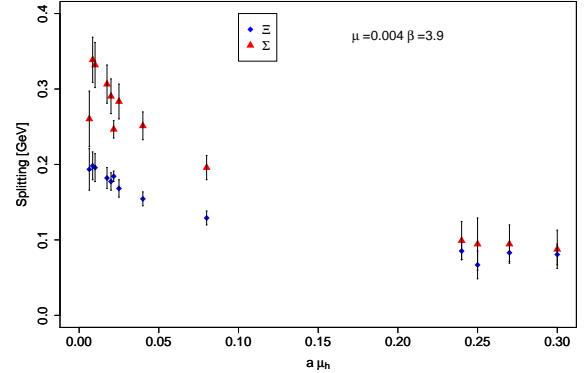


Figure 2: Σ/Σ^* and Ξ/Ξ^* splittings as function of m_h .

Hadron masses M_H are extracted from the two point correlation functions $C_H(t) = \sum_{\mathbf{x}} \langle H(t, \mathbf{x}) H^\dagger(0, \mathbf{0}) \rangle$ of the corresponding interpolating operators H at large time distances. In this region, the correlation functions decay exponentially at a rate proportional to the mass of the hadron. The value of the mass can be extracted for example by defining the effective mass $M_H^{\text{eff}}(t) = \frac{1}{a} \ln \frac{C_H(t)}{C_H(t+a)}$ and fitting it to a constant in the region of large time distances where the excited states have already decayed.

It turns out that the statistical error on $M_H^{\text{eff}}(t)$ for the strange baryons grows faster in time than in the case of the charmed baryons. In the case of the Ω_{sss} and Ω_{ccc} this is illustrated in Fig. 3.

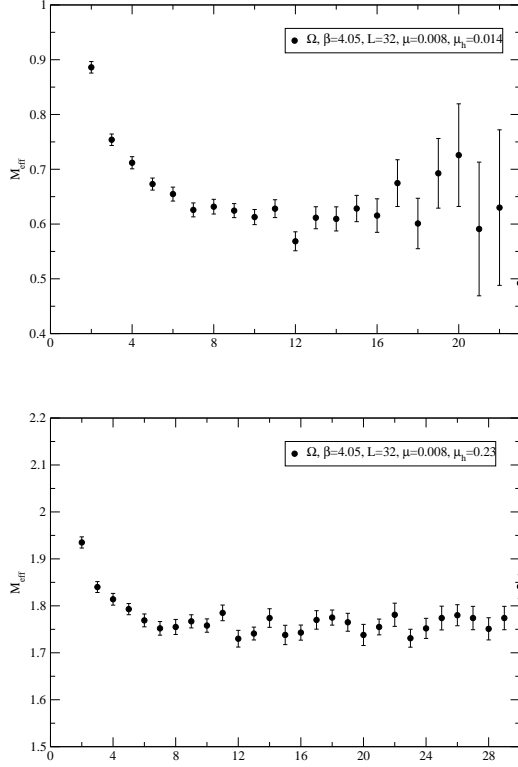


Figure 3: $M_{\Omega_{SSS}}^{\text{eff}}(t)$ (above) and $M_{\Omega_{ccc}}^{\text{eff}}(t)$ (below)

It is easy to prove that the statistical error on $M_{\Omega_{hhh}}^{\text{eff}}(t)$ is

$$\Delta M_{\Omega_{hhh}}^{\text{eff}}(t) \propto \exp(M_{\Omega_{hhh}} - \frac{3}{2}M_{\bar{h}h})t \quad (1)$$

where $M_{\bar{h}h}$ is the mass of the $\bar{h}h$ meson made of an heavy and an anti-heavy quark. This phenomenon is thus explained thanks to the observation that the ratio $M_{cc}/M_{\Omega_{ccc}}$ has a larger value than $M_{ss}/M_{\Omega_{sss}}$.

3.1. Ω_{SSS} and Ω_{ccc}

In Fig. 4 we present all the 40 data points for the Ω mass fitted with a form $M_{\Omega} = \bar{M}_0 + \bar{A}M_{\pi}^2 + \bar{B}M_{hl}^2 + \bar{C}M_{hl}^4$. The $\chi_{\text{d.o.f.}}^2$ is 1.87 and there is almost no evidence of lattice artefacts. This functional form is used only because it reduces to the form $M_{\Omega} = M_0 + AM_{\pi}^2 + BM_{hl}^2$ in the strange region while in the charm region it approximates fairly well the form $M_{\Omega} = D + EM_{\pi}^2 + FM_{hl}$. The two forms fit well the data in the strange region (13 data points, $\chi_{\text{d.o.f.}}^2 = 1.56$) and charm region (27 data points, $\chi_{\text{d.o.f.}}^2 = 1.15$) respectively.

In the strange region lattice artefacts are visible and the inclusion of a term A_0a^2 to the functional form above lower the $\chi_{\text{d.o.f.}}^2$ from 1.56 to 0.92. No sign of lattice artefacts is visible instead in the charm region. This is

however due to the choice of studying the behaviour of baryon masses as function of meson masses. Had we chosen to study their dependence upon the quark masses m_l and m_h we would have immediately remarked the presence of lattice artefacts (larger in the charm region). This is evident from the plot in Fig. 5 and in fact a fit of the form $M_{\Omega} = D + Em_l + Fm_h$ which does not include lattice artefacts has a huge $\chi_{\text{d.o.f.}}^2 = 141$ while by including a term D_0a^2 one obtains a reasonably good fit with $\chi_{\text{d.o.f.}}^2 = 1.07$. The same is valid in the strange region where the $\chi_{\text{d.o.f.}}^2$ reduces from 3.86 to 1.10.

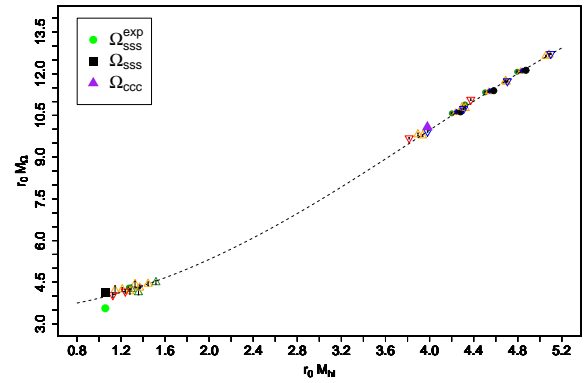


Figure 4: M_{Ω} as function of M_{hl} . The dashed line is a fit of the form $M_{\Omega} = \bar{M}_0 + \bar{A}M_{\pi}^2 + \bar{B}M_{hl}^2 + \bar{C}M_{hl}^4$

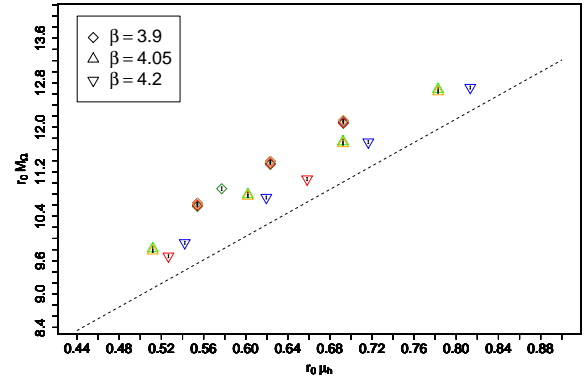


Figure 5: M_{Ω} as function of m_h in the charm region. The dashed line is the continuum limit according to the fit form $M_{\Omega} = D + Em_l + Fm_h + D_0a^2$ after setting $a = 0$ and m_l to some reference value.

We remark that M_{Ω} depends very mildly on M_{π} and therefore the extrapolation to the physical M_{π} seems not to pose any problem. By interpolating also to the physical value of M_K we get the result $M_{\Omega} = 1.86(20)$ GeV which is 10% larger than the experimental value. Due to the previous considerations and the analysis performed, this discrepancy seems not to be related to the continuum limit extrapolation or to the extrapolation in the light quark mass. Extrapolation to the physical

(M_π, M_D) point gives instead $M_{\Omega_{ccc}} = 4.73(40)$ GeV for which an experimental value is still missing.

3.2. Λ_{uds} and Λ_{udc}

In the case of the Λ baryon, the dependence on M_π is much stronger than in the previous case and the inclusion of the term proportional to M_π^3 is crucial and reduces the $\chi^2_{\text{d.o.f.}}$ of a factor ~ 0.5 in both the strange and the charm region. Lattice artefacts are hardly visible and the functional forms we have used to fit are $M_\Lambda = M_0 + AM_\pi^2 + BM_{hl}^2 + CM_\pi^3$ (in the strange region) and $M_\Lambda = D + EM_\pi^2 + FM_{hl}^2 + GM_\pi^3$ (in the charm region). Of course the inclusion of chiral logarithms would affect the extrapolation to the physical point. For these preliminary results we have however neglected them and performed only a rough fit using the forms written above. The dependence on M_π is shown (in the charm region) in Fig. 6

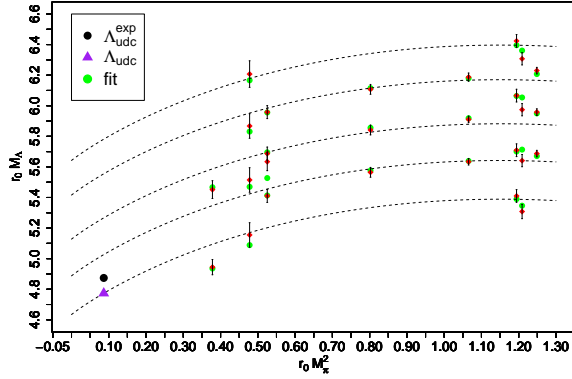


Figure 6: $M_{\Lambda_{udc}}$ as function of M_π^2 . The curves correspond to fits of the form $M_{\Lambda_{udc}} = D + EM_\pi^2 + FM_{hl}^2 + GM_\pi^3$. They are obtained by fixing M_{hl} to some values which are in general different to those of the data points.

By extrapolating to the physical (M_π, M_K) point we obtain $M_{\Lambda_{uds}} = 1.20(10)$ GeV which has to be compared with the experimental value $M_{\Lambda_{uds}}^{\text{exp}} = 1.116$ GeV. By extrapolating to the physical (M_π, M_D) point we have $M_{\Lambda_{udc}} = 2.24(18)$ GeV which is in good agreement with the experimental value $M_{\Lambda_{udc}}^{\text{exp}} = 2.286$ GeV.

3.3. Ξ_{dss} and Ξ_{dcc}

Twisted mass QCD breaks explicitly isospin symmetry and thus Ξ_{uss}^0 and Ξ_{dss}^- (or equivalently Ξ_{ucc}^{++} and Ξ_{dcc}^+) are not degenerate. We thus perform a combined fit of both Ξ_{uss}^0 and Ξ_{dss}^- data with the form $M_{\Xi(0,-)} = M_0 + AM_\pi^2 + BM_{hl}^2 + CM_\pi^3 + A_{(0,-)}a^2$ where the coefficients $A_{(0,-)}$ are different for the two sets of data. Analogously we perform a combined fit of both Ξ_{ucc}^{++} and Ξ_{dcc}^+ data with the form $M_{\Xi(++,+)} = D + EM_\pi^2 + FM_{hl}^2 + GM_\pi^3 + D_{(++,+)}a^2 + F_{(++,+)}a^2M_{hl}$. As in the Λ case a term in M_π^3

is needed even though the dependence on M_π is here less pronounced. Fits work well and in the continuum limit, at the physical point we get $M_{\Xi_{dss}} = 1.37(12)$ GeV (to be compared with $M_{\Xi_{dss}}^{\text{exp}} = 1.32$ GeV) and $M_{\Xi_{dcc}} = 3.52(25)$ GeV (in perfect agreement with $M_{\Xi_{dcc}}^{\text{exp}} = 3.52$ GeV).

4. Conclusions

In this preliminar study we have shown that lattice artefacts are always small in both the strange and the charm region when baryon masses are analyzed as function of meson masses. They are instead clearly visible when baryon masses are analyzed as function of quark masses. The chiral extrapolation in the light quarks confirms to be critical and a term of order M_π^3 is needed for both Ξ and Λ (it is particularly evident in this last case). $M_{\Omega_{ccc}}$ is still 10% larger than the experimental value and the source of this discrepancy seems not to be related to the continuum limit extrapolation or to the extrapolation in the light quark mass. Further investigations are needed to clarify this issue. Results for $M_{\Xi_{dss}}$, $M_{\Lambda_{uds}}$, $M_{\Xi_{dcc}}$ and $M_{\Lambda_{udc}}$ nicely agree with the experimental values. We have moreover obtained a prediction for $M_{\Omega_{ccc}} = 4.73(40)$ GeV. We are extending this preliminary analysis to the other strange and charmed baryons and also computing correlation functions to extract strange-charmed baryons. A complete analysis will be performed in the next future.

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